UTILITY PATENT APPLICATION TRANSMITTAL

(Only for new non-provisional applications under 37 CFR 1.53(b))

Attorney Docket No.	**Al-Dhahir 2**
First Named Inventor or Application Identifier	**Naofal Al-Dhahir**
Title	**Finite-Length Multi-Input Multi-Output Channel Shortening Pre-filters**
Express Mail Label no.	**EK795292892US**

To: **Assistant Commissioner for Patents**
Box Patent Application
Washington D.C. 20231

APPLICATION ELEMENTS	ACCOMPANYING APPLICATION PARTS
☒ Fee Transmittal Form (original and duplicate)	☒ Assignment
☒ Specification Total Pages **13**	☒ Recordation form
title	☒ Power of Attorney
cross reference to related applications (e.g. provisional application)	☒ Postcard
background	☐ Small entity statement
summary	☐ Certified copy of priority documents
brief description of the drawings (if filed)	☐ Information disclosure statement
detailed description	☐ Copies of IDS citations
claims	☐ 37 CFR 3.73(b) Statement
abstract	☒ check
☒ Drawing(s) Total Pages **3**	☐ Other
☒ Declaration Total Pages **2**	

a. ☐ Newly executed

b. ☐ Copy from a prior application (37 CFR 1.63(d))
   (for continuations/divisionals with section below filled out)

   ☐ Deletion of Inventor(s)   Signed Statement attached deleting inventor(s) named in the prior application. 37 CFR 163 (d)(2) and 1.33(b).

☐ Incorporation by reference (usable if Declaration is a copy):
The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied, is considered as being part of the disclosure of the accompanying application is hereby incorporated by reference herein.

☐ Other

If a CONTINUING APPLICATION, check appropriate box and supply the requisite information:

☐ Continuation   ☐ Divisional   ☐ Continuation-in-part (CIP) of prior Application No:

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Date	9/22/00

I hereby certify that this Application is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10 on the date indicated above and is addressed to the Assistant Commissioner for Patents, Washington D.C. 20231.

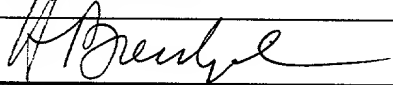| 9/22/00	Henry Brendzel	*(signature)*
Date of Deposit	(Printed Name of Person Mailing Paper)	(Signature of Person Mailing Paper)

FEE TRANSMITTAL

Patent Fees are subject to annual revisions on October 1
These are the fees effective November 10, 1998
Small entity payments must be supported by a small entity statement,
Otherwise, large entity fees must be paid. See Forms PTO/SB/09-12.

Complete if Known

Application Number	60/158,713
Filing Date	10/8/99
First Named Inventor	Naofal Al-Dhahir
Examiner Name	
Group/Art Unit	

TOTAL AMOUNT OF PAYMENT	($) 730	Attorney Docket ID	Al-Dhahir 2

METHOD OF PAYMENT (check one)

1. The Commissioner is hereby authorized to charge indicated fees and other underpayments, and credit overpayments to:

Deposit Account Number

500732

Deposit Account Name

Henry T. Brendzel

☒ Charge any additional Fee Required under 37 CFR 1.16 and 1.17

☐ Charge the Issue Fee Set in 37 CFR 1.18 at the Mailing of the Notice of Allowance

2. ☐ Payment enclosed:

☐ Check ☐ Money Order ☐ Other

FEE CALCULATION

1. FILING FEE

Fee Description		Fee Paid
Utility Filing Fee	. . . .	690
Design Filing Fee	. . . .	
Plant Filing Fee	. . . .	
Reissue Filing Fee	. . . .	
Provisional Filing Fee	. . . .	
SUBTOTAL (1) ($)		690

2. CLAIMS

	Claims remaining	Highest Paid	Extra	Rate	Amount
Total Claims	18	20	0	18	0
Independent Claims	1	3	0	78	0
Multiply Dependent Claims			☐	260	0
SUBTOTAL (2) ($)					0

FEE CALCULATION (continued)

3. ADDITIONAL FEES

Fee Description	Fee Paid
Surcharge – late filing fee or oath	
Surcharge – late provisional filing fee or cover sheet	
Non-English specification	
For filing request for reexamination	
Requesting publication of SIR prior to Examiner action	
Requesting publication of SIR after Examiner action	
Extension for reply within the first month	
Extension for reply within the second month	
Extension for reply within the third month	
Extension for reply within the fourth month	
Extension for reply within the fifth month	
Notice of Appeal	
Filing a brief in support of an appeal	
Requesting an oral hearing	
Petition to institute a public use proceeding	
Petition to revive - unavoidable	
Petition to revive - unintentional	
Utility issue fee (or reissue)	
Design issue fee	
Plant issue fee	
Petitions to the Commissioner	
Petitions related to provisional applications	
Submission of Information Disclosure Statement	
Recording each patent assignment per property (times number of properties)	40
Filing a submission after final rejection (37 CFR1.129(a))	
For each additional invention to be examined (37 CFR 1.129(b))	
Other fee	
Other fee	
SUBTOTAL (2) ($)	40

SUBMITTED BY

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			Reg. Number	26,844
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Application Information

Title Line One::	Method and Apparatus for Designing

Finite-Length Multi-Input Multi-Output Channel Shortening pre-filters

Total Drawing Sheets::	
Formal Drawings?::	Yes
Application Type::	

Continuity Information

This application is a::	converted utility application of Provisional
> Application One::	60/158,713
Filing Date::	October 8, 1999

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Finite-Length Multi-Input Multi-Output
Channel Shortening Pre-filters

Related Application:

5   This application claims priority from Provisional application No. 60/158,713 filed on October 8, 1999. This application is also related to a Provisional application No. 60/158,714, also filed on October 8, 1999.

Background of the Invention:

10   The combination of maximum likelihood sequence estimation (MLSE) with receiver diversity is an effective technique for achieving high performance over noisy, frequency-selective, fading channels impaired by co-channel interference. With the addition of transmitter diversity, the resulting multi-input multi-output (MIMO) frequency-selective channel has a significantly higher capacity than its

15 single-input multi-output (SIMO) or single-input single-output (SISO) counterparts. The use of maximum likelihood multi-user detection techniques on these frequency-selective MIMO channels significantly outperforms single-user detection techniques that treat signals from other users as colored noise. However, MLSE complexity increases exponentially with the number of inputs (or transmit

20 antennas) and with the memory of the MIMO channel, making its implementation over sever inter-symbol interference (ISI) channels very costly.

   The MIMO channel can be modeled as a collection of FIR filters (i.e., an FIR filter between each input point (e.g., transmitting antenna) and each receiving point (e.g. receiving antenna), and the "memory of the channel" corresponds to the

25 number of taps in the FIR filters.

   The Discrete Matrix Multitone (DMMT) was shown to be a practical transceiver structure that asymptotically achieves the MIMO channel capacity when combined with powerful codes. It uses the Discrete Fourier Transform (DFT) to partition the frequency responses of the underlying frequency-selective

30 channels of the MIMO systems into a large number of parallel, independent, and (approximately) memoryless frequency subchannels. To eliminate inter-block and intra-block interference, a cyclic prefix whose length is equal to the MIMO channel

memory is inserted in every block. On severe-ISI MIMO channels, the cyclic prefix overhead reduces the achievable DMMT throughput significantly, unless a large FFT size is used which, in turn, increases the computational complexity, processing delay, and memory requirements in the receiver.

In short, the computation complexity increases exponentially with the number of taps in the FIR filters that may be used to model the channel.

N. Al-Dhahir and J. M. Cioffi, in "Efficiently-Computed Reduced-Parameter Input-Aided MMSE Equalizers for ML Detection: A Unified Approach," IEEE Trans. Information Theory, pp. 903-915, May 1996, disclose use of a time-domain pre-filter in the receiver to shorten the effective channel memory and hence reduce the cyclic prefix overhead and/or the number of MLSE states. The disclosed approach, however, is for SISO systems, and not for MIMO systems.

Summary

An advance in the art is realized with a MIMO pre-filter that is constructed from FIR filters with coefficients that are computed based on environment parameters that are designer-chosen. Given a transmission channel that is modeled as a set of FIR filters with memory v, a matrix $\mathbf{W}$ is computed for a pre-filter that results in an effective transmission channel $\mathbf{B}$ with memory N_b, where $N_b < v$, where $\mathbf{B}$ is optimized so that $\mathbf{B}_{opt} = \text{argmin}_B\ trace(\mathbf{R}_{ee})$ subject to selected constraints; $\mathbf{R}_{ee}$ being the error autocorrelation function. The coefficients of $\mathbf{W}$, which are sensitive to a variety of designer constraints, are computed by a processor within pre-filter at the front end of a receiver and loaded into an array of FIR filters that form the pre-filter.

Brief Description of the Drawing

FIG. 1 shows the major elements of a receiver in accord with the principles disclosed herein;

FIG. 2 presents the structure of pre-filter 30; and

FIG. 3 is a flowchart describing the method carried out by processor 220 within pre-filter 30.

Detailed Description

FIG. 1 depicts the general case of an arrangement with n_q transmitting antennas 11-1, 11-2, ... 11-n_q, that output signals (e.g., space-time encoded

5   signals) to a transmission channel, and n_o receiving antennas 21-1, 21-2, ... 21-n_o. Each transmitting antenna p outputs a complex-valued signal x_p, the signals of the n_q antennas pass through a noisy transmission channel, and the n_o receiving antennas capture the signals that passed through the transmission channel. The received signals are oversampled by a factor of I in element 20 and applied to pre-

10   filter 30. Thus, the sampling clock at the output of element 20 is of period $T_s=T/I$, where T is the inter-symbol period at the transmitting antennas. The transmission channel's characterization is also referenced to T_s. In the illustrative embodiment disclosed herein, therefore, pre-filter 20 develops n_i output signals that are applied to a conventional multi-input receiver 40, and the received signal can be

15   expressed by

$$y_k^{(j)} = \sum_{i=1}^{N} \sum_{m=0}^{v^{(i,j)}} h_m^{(i,j)} x_{k-m}^{(i)} + n_k^{(j)} , \tag{1}$$

where $y_k^{(j)}$ is the signal at time k at the jth receiving antenna, $h_m^{(i,j)}$ is the mth coefficient (tap) in the channel impulse response between the ith transmitting antenna and the jth receiving antenna, and $\mathbf{n}^{(j)}$ is the noise vector at the jth

20   receiving antenna. The memory of this path (i.e., the largest value of m for which $h_m^{(i,j)}$ is not zero) is denoted by $v^{(i,j)}$. It not unreasonable to assume, however, that the memory of the transmission channel is the same for all i,j links ($n_i \times n_o$ such links), in which case $v^{(i,j)} = v$. Alternatively, the $v^{(i,j)}$ limit in equation (1) can be set to that v which corresponds to maximum length of all of the $n_i \times n_o$ channel

25   input responses, i.e., $v = \max_{i,j} v^{(i,j)}$. All of these variables in equation (1) are actually $I \times 1$ column vectors, corresponding to the I time samples per symbol in the oversampled FIG. 1 arrangement. By grouping the received samples from all

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n_o antennas at symbol time k into an $n_o l \times 1$ column vector $\mathbf{y}_k$, one can relate $\mathbf{y}_k$ to the corresponding $n_i \times 1$ (column) vector of input samples as follows

$$\mathbf{y}_k = \sum_{m=0}^{v} \mathbf{H}_m \mathbf{x}_{k-m} + \mathbf{n}_k , \tag{2}$$

where $\mathbf{H}_m$ is the MIMO channel coefficients matrix of size $n_o l \times n_i$, $\mathbf{x}_{k-m}$ is a size $n_i \times 1$ input (column) vector, and $\mathbf{n}_k$ is a size $n_o l \times 1$ vector.

Over a block of N_f symbol periods, equation (2) can be expressed in matrix notation as follows:

$$\begin{bmatrix} \mathbf{y}_{k+N_f-1} \\ \mathbf{y}_{k+N_f-2} \\ \vdots \\ \mathbf{y}_k \end{bmatrix} = \begin{bmatrix} \mathbf{H}_0 & \mathbf{H}_1 & \cdots & \mathbf{H}_v & 0 & \cdots & 0 \\ 0 & \mathbf{H}_0 & \mathbf{H}_1 & \cdots & \mathbf{H}_v & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \mathbf{H}_0 & \mathbf{H}_1 & \cdots & \mathbf{H}_v \end{bmatrix} \begin{bmatrix} \mathbf{x}_{k+N_f-1} \\ \mathbf{x}_{k+N_f-2} \\ \vdots \\ \mathbf{x}_{k-v} \end{bmatrix} + \begin{bmatrix} \mathbf{n}_{k+N_f-1} \\ \mathbf{n}_{k+N_f-2} \\ \vdots \\ \mathbf{n}_k \end{bmatrix} \tag{3}$$

or, more compactly,

$$\mathbf{y}_{k+N_f-1:k} = \mathbf{H}\mathbf{x}_{k+N_f-1:k-v} + \mathbf{n}_{k+N_f-1:k} . \tag{4}$$

The subscripts in equation (4) indicate a range. For example $k + N_f - 1 : k$ indicates the range $k + N_f - 1$ and k, inclusive.

It is useful to define the following correlation matrices:

$$\mathbf{R}_{xy} \equiv E[x_{k+N_f-1:k-v} y^*_{k+N_f-1:k}] = \mathbf{R}_{xx}\mathbf{H}^* \tag{5}$$

$$\mathbf{R}_{yy} \equiv E[y_{k+N_f-1:k} y^*_{k+N_f-1:k}] = \mathbf{H}\mathbf{R}_{xx}\mathbf{H}^* + \mathbf{R}_{nn} , \tag{6}$$

$$\mathbf{R}_{xx} \equiv E[x_{k+N_f-1:k-v} x^*_{k+N_f-1:k-v}] \text{ and} \tag{7}$$

$$\mathbf{R}_{nn} \equiv E[n_{k+N_f-1:k} n^*_{k+N_f-1:k}] . \tag{8}$$

It is assumed that these correlation matrices do not change significantly in time or, at least, do not change significantly over a time interval that corresponds to a TDMA burst (assumed to be much shorter than the channel coherence time), which is much longer than the length of the pre-filter, in symbol periods denoted by N_f. Accordingly, a re-computation of the above matrices, and the other parameters disclosed herein, leading to the computation of pre-filter coefficients, need not take place more often than once every TDMA burst.

Once **H**, $\mathbf{R}_{xx}$ and $\mathbf{R}_{nn}$ and known, $\mathbf{R}_{xy}$ and $\mathbf{R}_{yy}$ are computed by $\mathbf{R}_{xx}\mathbf{H}^*$ and $\mathbf{HR}_{xx}\mathbf{H}^* + \mathbf{R}_{nn}$, respectively.

Given the MIMO channel matrix **H** with $v+1$ members $(\mathbf{H}_0, \mathbf{H}_1, \cdots \mathbf{H}_v)$, the objective is to create a MIMO pre-filter **W** (element 30 in FIG. 1) with N_f matrix taps, i.e., matrix $\mathbf{W} \equiv \begin{bmatrix} \mathbf{W}_0 & \mathbf{W}_1 & \cdots & \mathbf{W}_{N_f-1} \end{bmatrix}^T$, that equalizes **H** so as to create an overall transmission channel for receiver 40 that corresponds to a matrix **B** with memory N_b, where $N_b \ll v$.

The matrix **B** can be expressed as $\mathbf{B} \equiv \begin{bmatrix} \mathbf{B}_0 & \mathbf{B}_1 & \cdots & \mathbf{B}_{N_b} \end{bmatrix}^T$ where each $\mathbf{B}_i$ is of size $n_i \times n_i$.

The MIMO channel-shortening pre-filter **W** (element 30) is conditioned, or adjusted, to minimize the equalization Mean Squared Error (MSE), defined by $MSE \equiv trace(\mathbf{R}_{ee})$, where $\mathbf{R}_{ee}$ is the autocorrelation matrix of the error vector $\mathbf{E}_k$ that is given by

$$\mathbf{E}_k = \tilde{\mathbf{B}}^* \mathbf{x}_{k+N_f-1:k-v} - \mathbf{W}^* \mathbf{y}_{k+N_f-1:k}, \tag{9}$$

where the augmented MIMO matrix, $\tilde{\mathbf{B}}^*$, is

$$\tilde{\mathbf{B}}^* \equiv \begin{bmatrix} 0_{n_i \times n_i\Delta} & \mathbf{B}_0^* & \mathbf{B}_1^* & \cdots & \mathbf{B}_{N_b}^* & 0_{n_i \times n_i s} \end{bmatrix} \equiv \begin{bmatrix} 0_{n_i \times n_i\Delta} & \mathbf{B}^* & 0_{n_i \times n_i s} \end{bmatrix}, \tag{10}$$

Δ is the decision delay that lies in the range $0 \le (N_f + v - N_b - 1)$, and $s \equiv N_f + v - N_b - \Delta - 1$. The $n_i \times n_i$ error autocorrelation function $\mathbf{R}_{ee}$ can be expressed by the following:

$$\begin{aligned} \mathbf{R}_{ee} &\equiv E[\mathbf{E}_k \mathbf{E}_k^*] \\ &= \tilde{\mathbf{B}}^* (\mathbf{R}_{xx} - \mathbf{R}_{xy}\mathbf{R}_{yy}^{-1}\mathbf{R}_{yx})\tilde{\mathbf{B}} \\ &= \tilde{\mathbf{B}}^* \mathbf{R}^\perp \tilde{\mathbf{B}} \\ &= \tilde{\mathbf{B}}^* \bar{\mathbf{R}} \mathbf{B}, \end{aligned} \tag{11}$$

where $\bar{\mathbf{R}}$ is a sub-matrix of $\mathbf{R}^\perp$ determined by Δ.

Using the orthogonality principle, which states that $E[\mathbf{E}_k \mathbf{y}_{k+N_f-1:k}^*] = 0$ it can be shown that the optimum channel-shortening pre-filter and target impulse response filters (**W** and **B**, respectively) are related by

$$\begin{aligned}
\mathbf{W}_{opt}^* &= \tilde{\mathbf{B}}_{opt}^* \mathbf{R}_{xy} \mathbf{R}_{yy}^{-1} \\
&= \tilde{\mathbf{B}}_{opt}^* \mathbf{R}_{xx} \mathbf{H}^* (\mathbf{H} \mathbf{R}_{xx} \mathbf{H}^* + \mathbf{R}_{nn})^{-1} \\
&= \tilde{\mathbf{B}}_{opt}^* (\mathbf{R}_{xx}^{-1} + \mathbf{H}^* \mathbf{R}_{nn}^{-1} H)^{-1} \mathbf{H}^* \mathbf{R}_{nn}^{-1}.
\end{aligned} \tag{12}$$

The last line shows explicitly that the MIMO channel-shortening pre-filter consists of a noise whitener $\mathbf{R}_{nn}^{-1}$, a MIMO matched filter $\mathbf{H}^*$, and a bank of FIR channel-shortening pre-filter elements.

It remains to optimize $\tilde{\mathbf{B}}$ such that the MSE is minimized, which may be obtained by computing the parameters of $\mathbf{B}$ that, responsive to specified conditions, minimizes the trace (or determinant) of $\mathbf{R}_{ee}$. The following discloses two approaches to such optimization.

Under one optimization approach the coefficients of $\mathbf{B}$ are constrained so that some coefficient of $\mathbf{B}$ is equal to the identity matrix, $\mathbf{I}$. A solution subject to this Identity Tap Constraint (ITC) can be expressed by

$$\mathbf{B}_{opt}^{ITC} = \arg\min_B \ trace(\mathbf{R}_{ee}) \text{ subject to } \mathbf{B}^* \boldsymbol{\Phi} = \mathbf{I}_{n_i}, \tag{13}$$

where $\boldsymbol{\Phi}^* \equiv \begin{bmatrix} \mathbf{0}_{n_i \times n_i m} & \mathbf{I}_{n_i} & \mathbf{0}_{n_i \times n_i (N_b - m)} \end{bmatrix}$ and $0 \le m \le N_b$. It can be shown that the optimum MIMO target impulse response and the corresponding error autocorrelation matrix are given by

$$\mathbf{B}_{opt}^{ITC} = \bar{\mathbf{R}}^{-1} \boldsymbol{\Phi} (\boldsymbol{\Phi}^* \bar{\mathbf{R}}^{-1} \boldsymbol{\Phi})^{-1} \text{ and} \tag{14}$$

$$\mathbf{R}_{ee,min}^{ITC} = (\boldsymbol{\Phi}^* \bar{\mathbf{R}}^{-1} \boldsymbol{\Phi})^{-1}. \tag{15}$$

As indicated above, $\bar{\mathbf{R}}$ is affected by the delay parameter Δ. Unless dictated by the designer, the delay parameter Δ, which can range between 0 and $(N_f + v - N_b - 1)$, is chosen to minimize the trace of $\mathbf{R}_{ee,min}^{ITC}$. Similarly, the index parameter m, which ranges between 0 and N_b, and which that affects $\boldsymbol{\Phi}$, is chosen to minimize the trace of $\mathbf{R}_{ee,min}^{ITC}$.

Under a second optimization approach the imposed constraint is $\mathbf{B}^* \mathbf{B} = \mathbf{I}_{n_i}$. A solution subject to this Ortho-Normality Constraint (ONC) can be expressed by

$$\mathbf{B}_{opt}^{ONC} = \arg\min_B \ trace(\mathbf{R}_{ee}) \text{ subject to } \mathbf{B}^* \mathbf{B} = \mathbf{I}_{n_i}, \tag{16}$$

Defining the eigen-decomposition

$$\bar{\mathbf{R}} \equiv \mathbf{U}\mathbf{\Sigma}\mathbf{U}^* = \mathbf{U}diag(\sigma_0, \sigma_1 \cdots \sigma_{n,(N_b+1)-1})\mathbf{U}^*,\qquad(17)$$

where $\sigma_0 \geq \sigma_1 \cdots \geq \sigma_{n,(N_b+1)-1}$, then the optimum MIMO target response and the resulting error autocorrelation matrix are given by

$$\mathbf{B}_{opt}^{ONC} = \mathbf{U}\left[e_{n,N_b} \quad \cdots \quad e_{n,(N_b+1)-1} \right],\qquad(18)$$

where e_i is unit vector with a 1 at position i, and 0's elsewhere, and

$$\mathbf{R}_{ee,min}^{ONC} = diag(\sigma_{n,N_b}, \cdots, \sigma_{n,(N_b+1)-1}).\qquad(19)$$

Illustratively, if $n_i=3$ and $N_b=3$, $\mathbf{B}_{opt}^{ONC} = \mathbf{U}\left[e_9, e_{10}, e_{11} \right]$, meaning that $\mathbf{B}_{opt}^{ONC}$ is a three column matrix comprising the 9th through the 11th columns of matrix $\mathbf{U}$. Stated in words, the optimum MIMO target impulse response matrix is given by the n_i eigenvectors of $\bar{\mathbf{R}}$ that correspond to its n_i smallest eigenvalues. The delay parameter Δ $(0 \leq \Delta \leq N_f + v - N_b - 1)$ that affects $\bar{\mathbf{R}}$ is optimized to minimize the trace (or determinant) of $\mathbf{R}_{ee,min}^{ONC}$.

With the above analysis in mind, a design of a prefilter 30 can proceed for any given set of system parameters, which includes:

- MIMO channel memory between the input points and the output point of the actual transmission channel, v,
- The number of pre-filter taps chosen, N_f,
- The shortened MIMO memory, N_b,
- The number of inputs to the transmission channel, n_i,
- The number of output derived from the transmission channel, n_o,
- The autocorrelation matrix of the inputs, $\mathbf{R}_{xx}$,
- The autocorrelation matrix of the noise, $\mathbf{R}_{nn}$,
- The oversampling used, l, and
- The decision delay, Δ.

The structure of pre-filter 30 is shown in FIG. 2. In the illustrated embodiment, it comprises two main components: processor 220 and filter section 210.

Filter section 210 in the FIG. 2 illustrative example comprises a collection of FIR filters that connect the n_o input array of signals from sampling circuit 20 to an

n_i output array of points. That is, there are $j \times i$ FIR filters $P_{j,i}$, that couple input point j to output point i.

Processor 220 is responsive to the n_o signals received by antennas 21 and sampled by circuit 20, and it computes the coefficients of W, as disclosed above. W_0 is a matrix that defines the coefficients in the 0th tap of the $j \times i$ FIR filters, W_1 is a matrix that defines the coefficients in the 1st tap of the $j \times i$ FIR filters, etc.

The method of developing the parameters of pre-filter 30, carried out in processor 220, is shown in FIG. 3. Block 100 develops an estimate of the MIMO channel between the input points and the output point of the actual transmission channel. This is accomplished in a conventional manner through the use of training sequences. The estimate of the MIMO channel can be chosen to be limited to a given memory length, v, or can be allowed to include as much memory as necessary to reach a selected estimate error level. That, in turn, depends on the environment and is basically equal to the delay spread divided by T_s.

Following step 100, step 110 determines the matrices, R_{nn}, R_{xx}, R_{xy}, and R_{yy}. The matrix R_{nn} is computed by first computing $n = y - Hx$ and then computing the expected value $E[n^*n]$ -- see equation (8) above. The matrix R_{xx} is computed from the known training sequences -- see equation (7) above -- (or is pre-computed and installed in processor 220). In may be noted that for uncorrelated inputs, $R_{xx}=I$. The matrices R_{xy} and R_{yy} are computed from the known training sequences and the received signal or directly from H and R_{nn}-- see equations (5) and (6) above.

Following step 110, step 120 computes $R^\perp = R_{xx} - R_{xy}R_{yy}^{-1}R_{yx}$, and the sub-matrix $\bar{R}$. From equation (10) is can be seen that $\bar{R}$ is obtained by dropping the first $n_i\Delta$ rows and the last $n_i s$ rows of $R^\perp$.

In accordance with the ITC approach, selecting some value of $0 \le m \le N_b$ allows completion of the design process. Accordingly, following step 120, step 130 chooses a value for m, develops $\Phi^* \equiv \begin{bmatrix} 0_{n_i \times n_i m} & I_{n_i} & 0_{n_i \times n_i(N_b-m)} \end{bmatrix}$ and carries out

the computation of equation (13). Step 140 finally develops the coefficients of matrix W in accordance with equation (12), and installs the developed coefficients within filter 210.

In accordance with the ONC approach, step 130 computes the matrix **U** in a conventional manner, identifies the unit vectors e_i, and thus obtains the matrix **B**. Step As with the ITC approach, step 140 develops the coefficients of matrix W in accordance with equation (12), and installs the developed coefficients within filter 210.

It should be understood that a number of aspects of the above disclosure, for example, those related to the ITC constraint and to the ONC constraint, are merely illustrative, and that persons skilled in the art may make various modifications that, nevertheless, are within the spirit and scope of this invention. For example, the pre-filter described above generates a multi-output signal, with the number of outputs being n_i, that being also the number of transmitting antennas 11. This, however, is not a limitation of the principles disclosed herein. The number of pre-filter outputs can, for example, be larger than n_i, for example as high as $n_i(N_b +1)$. The performance of the receiver will be better with more filter outputs, but more outputs require more FIR filters, more FIR filter coefficients, and correspondingly, a greater processing power requirement placed on processor 220.

Claims:

1. A receiver responsive to an n_o plurality of antennas comprising:

a pre-filter having an $n_o \times n_i$ plurality of FIR filters, each responsive to a signal that is derived from one of said n_o antennas and applied to an input point, and each developing an output signal that contributes to one of n_i pre-filter outputs; and

decision logic responsive to said n_i outputs.

2. The receiver of claim 1 further comprising a sampling circuit interposed between said n_o plurality of antennas and said pre-*filter that samples received signal at rate* $T_s = \dfrac{T}{I}$, *where I is an integer and* T is symbol rate of a transmitter whose signals said receiver receives.

3. The receiver of claim 2 where $I>1$.

4. The receiver of claim 1 where coefficients of said FIR filters are computed in a processor in response to a block of N_f symbols.

5. The receiver of claim 4 where said processor is part of said pre-filter.

6. The receiver of claim 4 where said coefficients of said FIR filters are computed once every time interval during which transfer characteristics of said transmission channel, H, are substantially constant.

7. The receiver of claim 6 where said processor installs computed coefficients of said FIR filters in said FIR filters following each computation.

8. The receiver of claim **1** where said FIR filters form an array of filters, and said array has one FIR filter connected between each of said n_o input points and said n_i outputs.

9. The receiver of claim **8** where said n_o plurality of antennas receive signals, via said transmission channel, from a transmitter having a multiple number of transmitting antennas.

10. The receiver of claim **9** where said transmitter has n_i transmitting antennas.

11. The receiver of claim **10** wherein said decision logic is adapted to receive from said transmitted signals that were encoded in a space-time encoding schema.

12. The receiver of claim **2** where said plurality of FIR filters is expressed by matrix **W**, and **W** is computed by $\mathbf{W}_{opt}^* = \tilde{\mathbf{B}}_{opt}^* \mathbf{R}_{xy} \mathbf{R}_{yy}^{-1}$,

$\mathbf{W}_{opt}^* = \tilde{\mathbf{B}}_{opt}^* \mathbf{R}_{xx} \mathbf{H}^* (\mathbf{H} \mathbf{R}_{xx} \mathbf{H}^* + \mathbf{R}_{nn})^{-1}$, or $\mathbf{W}_{opt}^* = \tilde{\mathbf{B}}_{opt}^* (\mathbf{R}_{xx}^{-1} + \mathbf{H}^* \mathbf{R}_{nn}^{-1} \mathbf{H})^{-1} \mathbf{H}^* \mathbf{R}_{nn}^{-1}$, where $\mathbf{R}_{xx}$ is an autocorrelation matrix of a block of signals transmitted by a plurality of transmitting antennas to said n_o antennas via a channel having a transfer characteristic **H**, $\mathbf{R}_{nn}$ is an autocorrelation matrix of noise received by said plurality of n_o antennas during said block of signals transmitted by said transmitting antennas, $\mathbf{R}_{xy} = \mathbf{R}_{xx} \mathbf{H}^*$, $\mathbf{R}_{yy} = \mathbf{H} \mathbf{R}_{xx} \mathbf{H}^* + \mathbf{R}_{nn}$, and

$\tilde{\mathbf{B}}_{opt}^*$ is a sub-matrix of matrix $\mathbf{B}_{opt}^*$, where $\mathbf{B}_{opt} = \mathrm{argmin}_B \, trace(\mathbf{R}_{ee})$ subject to a selected constraint, $\mathbf{R}_{ee}$ being the error autocorrelation function.

13. The receiver of claim **12** wherein said plurality of FIR filters are subjected to designer constraints relative to any one or a number of members of the following set: transmission channel memory, size of said block, effective memory of the combination consisting of said transmission channel and said pre-

filter; n_i, n_o, autocorrelation matrix $\mathbf{R}_{xx}$, autocorrelation matrix $\mathbf{R}_{nn}$, value of factor l in said sampling circuit, and decision delay.

14. The receiver where said matrix $\mathbf{W}$ is expressible by

$$\mathbf{W} \equiv \begin{bmatrix} \mathbf{W}_0 & \mathbf{W}_1 & \cdots & \mathbf{W}_{N_f-1} \end{bmatrix}^t,$$ where matrix $\mathbf{W}_q$ is a matrix that specifies q^{th} tap coefficients of said FIR filters.

15. The receiver of claim **12** where said constraint restricts $\mathbf{B}$ so that $\mathbf{B}^*\mathbf{\Phi} = \mathbf{I}_{n_i}$, where $\mathbf{\Phi}^* \equiv \begin{bmatrix} \mathbf{0}_{n_i \times n_i m} & \mathbf{I}_{n_i} & \mathbf{0}_{n_i \times n_i (N_b-m)} \end{bmatrix}$ and m is a selected constant.

16. The receiver of claim **15** where $\mathbf{B} = \bar{\mathbf{R}}^{-1}\mathbf{\Phi}(\mathbf{\Phi}^*\bar{\mathbf{R}}^{-1}\mathbf{\Phi})^{-1}$, $\bar{\mathbf{R}}$ is a sub-matrix of a matrix $\mathbf{R}^{\perp} = \mathbf{R}_{xx} - \mathbf{R}_{xy}\mathbf{R}_{yy}^{-1}\mathbf{R}_{yx}$.

17. The receiver of claim **12** where said constraint restrict $\mathbf{B}$ so that $\mathbf{B}^*\mathbf{B} = \mathbf{I}_{n_i}$.

18. The receiver of claim **17** where $\mathbf{B} = \mathbf{U}\begin{bmatrix} e_{n_i N_b} & \cdots & e_{n_i(N_b+1)-1} \end{bmatrix}$, each element e_p is a vector having a 0 element in all rows other than row p, at which row the element is 1, and U is a matrix that satisfies the equation $\bar{\mathbf{R}} \equiv \mathbf{U}\mathbf{\Sigma}\mathbf{U}^*$, $\mathbf{\Sigma}$ being a diagonal matrix.

Abstract

A multi-input, multi-output pre-filter improves operation of a multi-input receiver by shortening the effective memory of the channel with a set of FIR filters. The coefficients of these FIR filters can be fashioned to provide a variety of

5   controls by the designer, for example, the value of the effective memory.

FIG. 1

FIG. 2

FIG. 3

100

| DEVELOPE CHANNEL ESTIMATE |

110

| COMPUTE R_{nn}, R_{xx}, R_{xy}, R_{yy} |

120

| COMPUTE $\bar{R}$, $\overset{\perp}{R}$ |

130

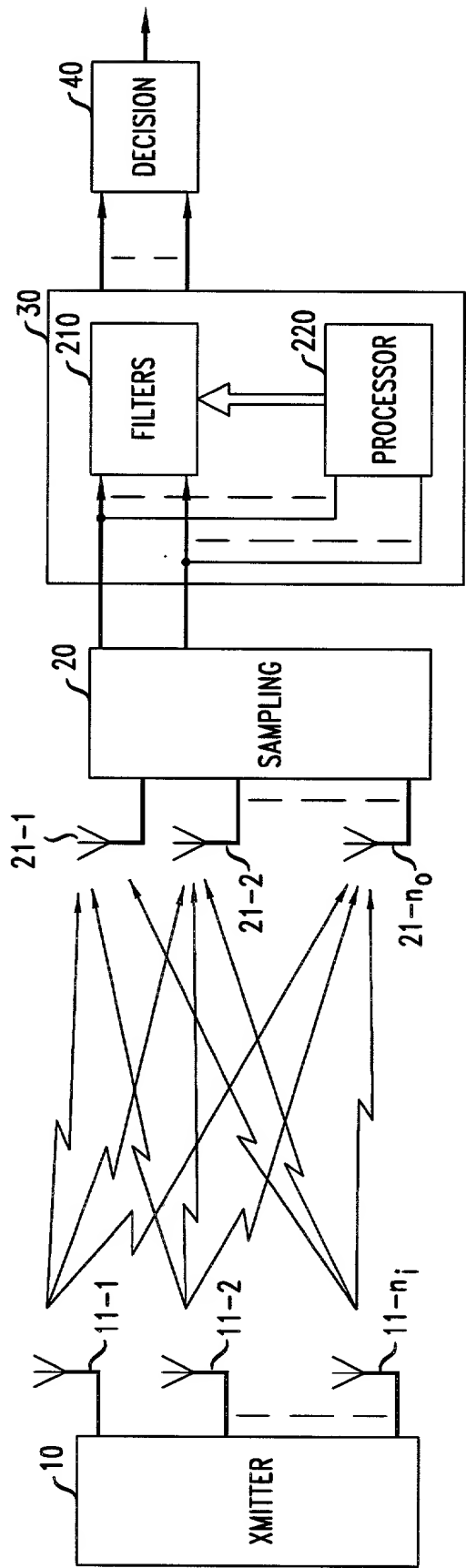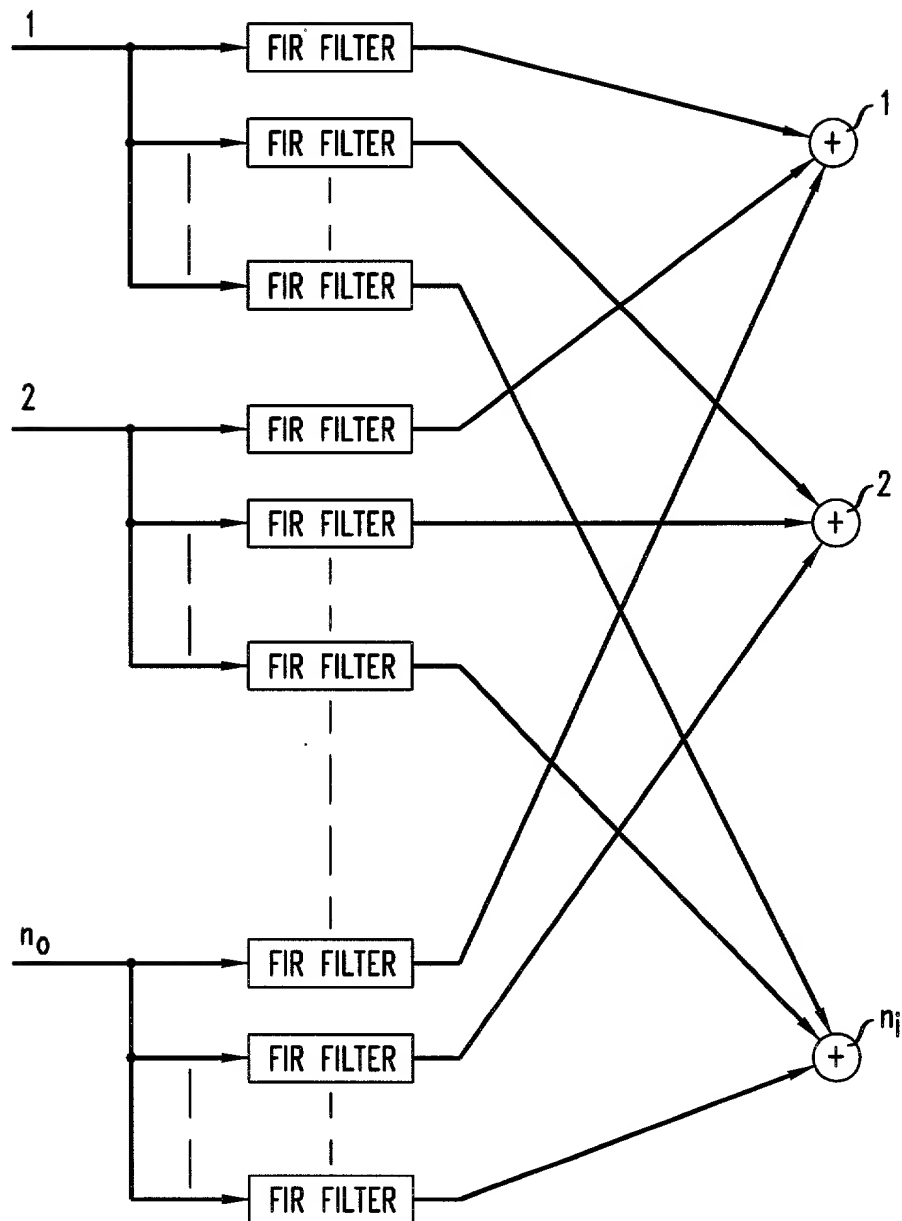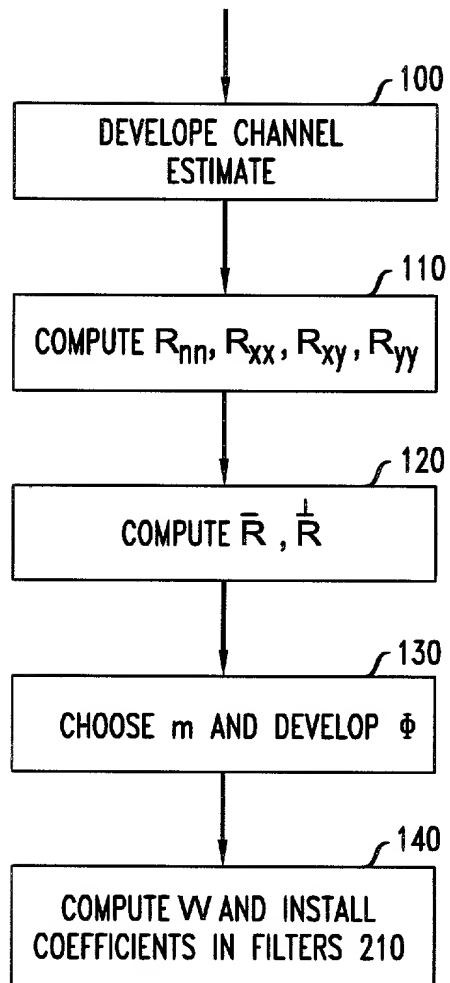| CHOOSE m AND DEVELOP ϕ |

140

| COMPUTE W AND INSTALL COEFFICIENTS IN FILTERS 210 |

IN THE UNITED STATES
PATENT AND TRADEMARK OFFICE

Declaration and Power of Attorney

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am an original, first and sole inventor of the subject matter which is claimed and for which a patent is sought on the invention entitled **Finite-Length Multi-Input Multi-Output Channel Shortening Pre-filters** the specification of which was filed on 10/8/99, as application Serial No. 60/158,713.

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by an amendment, if any, specifically referred to in this oath or declaration.

I acknowledge the duty to disclose all information known to me, which is material to patentability as defined in Title 37, Code of Federal Regulations, 1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, 119 of any foreign application(s) for patent or inventors' certificate listed below and have also identified below any foreign application for patent or inventors' certificate having a filing date before that of the application on which priority is claimed:

I hereby claim the benefit under Title 35, United States Code, 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, 112, we acknowledge the duty to disclose all information known to us to be material to patentability as defined in Title 37, Code of Federal Regulations, 1.56 which became available between the filing date of the prior application and the national or PCT international filing date of this application:

US Provisional application 60/158,713, filed October 8, 1999.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

I hereby appoint the following attorney(s) with full power of substitution and revocation, to prosecute said application, to make alterations and amendments therein, to receive the patent, and to transact all business in the Patent and Trademark Office connected therewith:

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I also appoint the following as associate attorney(s), with full power to prosecute said application, to make alternations and amendments therein, and to transact all business in the Patent and Trademark Office connected therewith:

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